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Human in the Loop: perceived-based control as the key to enhance buildings' performance

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Abstract

The Energy Performance Gap (EPG) is a phenomenon that both can be encountered in new and in refurbished buildings and potentially jeopardises the effort of making buildings more sustainable. Often, buildings are affected by a more generic "performance gap", meaning that, beside the EPG, also the comfort delivered to the occupants is not as requested.

In this work, we present a Human-in-the-Loop (HuiL) approach to control buildings. We developed a mobile app that allows occupants to provide their personal feedback about their indoor thermal sensation in real time, while monitoring their actual location within the building. Based on the thermal sensation votes, the system is capable of controlling the settings of smart thermostats in each room of a building. We tested the mobile app and a preliminary feedback-based manual control of the thermostats in a school building located in the Greater Copenhagen Area. Preliminary results show a higher comfort, when using the HuiL perception-based control approach: in particular, the answer "good", used to positively rate the indoor temperature, was chosen 50,9% of times in a period with standard set points, and 63,3% of times in a periodwhile the set points of the smart thermostats of the classrooms were chosen based on a HuiL perception-based control.

Key Innovations

- Going beyond set-point: paradigm shift with perception-based control of buildings
- Full automatic control of buildings with HuiL control to maximise occupants' comfort
- Live occupancy data for future Model Predictive Control and Flexibility activation
- Possibility to profile occupants and cluster them accordingly to their comfort requirements.

Practical Implications

Thanks to the here presented mobile app, occupants can rate the indoor climate in their exact location. The occupants are localised thanks to a low-cost Bluetooth Low Energy (BLE) beacon network, hence, for the occupants, the feedback procedure is very simple. Big office buildings, schools, public buildings, and even commercial buildings can finally allow occupants to interact with the building HVAC, instead of letting an undefined and variable group of them dealing with complex set points choices.

Introduction

In Northern Europe and USA, human beings spend more than 90% of their time in buildings (Prasad and Samuels, 2005; US EPA Office of Policy, Economics, and Innovation, 2009). We live in buildings, most of us work in buildings, and we even play sport in buildings. It is therefore not surprising, that we put high expectations on the built environment: The built environment should be comfortable, and the air should be clean (Calì 2016). However, a comfortable indoor environment and clean air in buildings comes at a cost: an intense use of energy. Despite this intense use of energy, buildings are still affected by the so-called Energy Performance Gap (Attia et al., 2013; Calì et al., 2016b; Fokaides et al., 2011; Magalhães and Leal, 2014; Menezes et al., 2012; Tronchin and Fabbri, 2008; De Wilde, 2014), broken occupants' expectations, and rebound effect (Berkhout et al., 2000; Calì and Müller, 2011; Galvin, 2015, 2014; Greening et al., 2000; Haas and Biermayr, 2000; Hens et al., 2010; Roels et al., 2017; Sunikka-Blank and Galvin, 2012). The three abovementioned phenomena can be referred to as "Buildings' Performance Gap" (BPG).

What's wrong with buildings? And: what is the way out of the BPG?

The performance gap of existing, retrofitted, and new buildings jeopardizes the effort to reach the decarbonization target.

We identify three major areas of interest that have to be addressed, if we want to minimize the BPG, and hence minimize the buildings high CO_2 emissions, and the number of dissatisfied occupants. Those areas are TRUST, EFFORT, and VOLATILITY. The first two areas are strictly related to the buildings' occupants, owners, and managers, while the third keyword is also related to the energy grid.

Trust & Effort

The annual retrofit rate of existing buildings in developed countries is generally around 1%. As a consequence, the building stock can only provide comfort conditions to their occupants, at a high energy cost.

At a first glance, we could erroneously think that people are not interested in comfort, nor in a good indoor environment. But, if we think of the car market, we discover that many recent cars have double climate control, air conditioning, and even heated seats and steering wheel. We can call it the "The High-tech car vs. Low-Tech house paradox" (Figure 1), or, in other words, "why we do treat ourselves as kings in our cars, as Neanderthals in buildings". The discrepancy between high-tech cars and low-tech houses is explained through Trust and Effort.

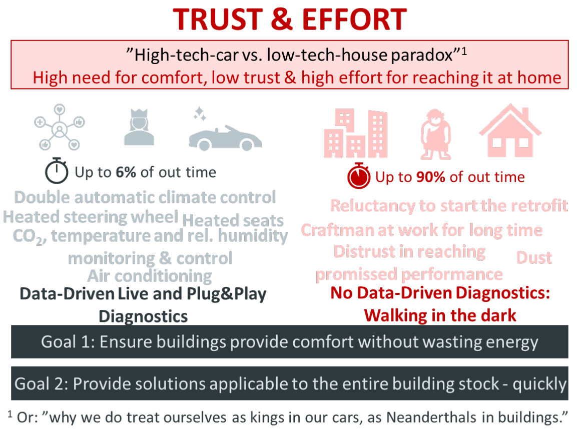

Figure 1 The High-tech car vs. Low-Tech house paradox

We trust that systems in cars will work together, that they will deliver the expected service, and we know one brand (the car-brand) guarantees that the components (produced from a number of different companies) will work and communicate together. On the contrary, in buildings we generally connect a retrofit to a big effort (craftsmen at work, dust) and we distrust that the building will reach the promised performance. As a consequence, we need tools that can evaluate, in real time, the performance of buildings: the first goal to mitigate the BPG is hence to be able to prove that buildings deliver the requested level of comfort without wasting energy. Ensuring this means being transparent about both indoor environment data and energy usage data of buildings. A transparent data handling could be key to get buildings' owners' trust. Secondly, to address the entire building stock, we need to develop scalable solutions that can quickly be rolled out, and hence have the lowest possible retrofit effort.

Volatility

The third aspect we should keep in mind when dealing with buildings is connected to volatility. Volatility in buildings is both on the usage side, as well as on the production side (Figure 2).

On the one hand, buildings are mostly planned and controlled based on assumptions and fixed schedules which might have been valid in the Sixties. However, our society evolved: For example, residential buildings where families live are often empty during the day while both parents go to work and children stay until afternoon at schools; in parallel, work-from-home became reality, also several times a week. On the other hand, not only is the demand for comfort volatile: to minimize buildings' impact on climate change, we must maximize the use of renewable energy sources. Consequently, the production of energy is non-projectable. Matching the volatile usage of buildings with intermittent energy production can help both enhancing personal comfort and reducing CO2 emissions caused by heating, ventilating, and cooling the existing building stock.

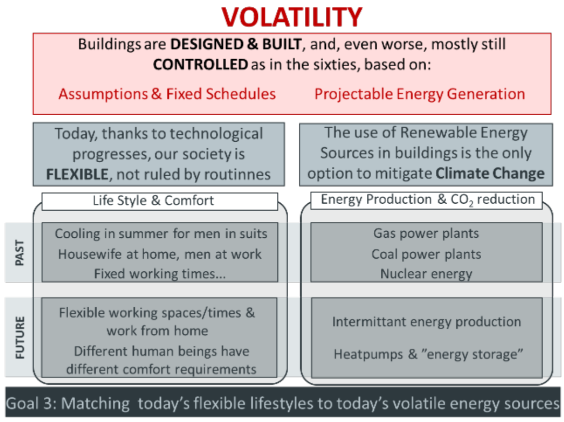

Figure 2 Volatility issue in buildings, and related goal

A path to solve the buildings' performance gap

The call for transparency is clear and cannot prescind from a valuable monitoring tool of the building performance. Moreover, the goals identified in the previous section call for a paradigm shift in the way we control buildings today. The fast developments in IoT and their potential integration in the built environment represents a big chance to transform legacy buildings into a Cyber Physical System (CPS) (Gil et al., 2020). Bavaresco et al. (2019) state the necessity to include the "human-dimension" into the control loop of buildings, which they identify as "Cyber Physical Social Systems" (CPSS). On the one hand, buildings handled as a CPS or a CPSS can easily integrate the human dimension through a human-in-the-loop perceived-based control. On the other hand, they can provide valuable data to understand issues, and find optimal solutions to address them.

Methods

In this section, we describe the building we adopted as a case-study and developed as a CPSS, in order to test our HuiL perceived based control platform, as well as the solution we propose to the "*TRUST, EFFORT and VOLATILITY*" issues.

Demonstration Case

In order to demonstrate the project, we selected an old building from a school (Lex et al., 2019) located in the Høje Taastrup Municipality, in the Greater Copenhagen Area in Denmark. The school building (Figure 3) was built at the beginning of the twentieth century and was, years ago, partially refurbished with new windows and a ventilation system. A total of 28 locations (10 classrooms, 2 meeting rooms, 1 office room, 8 open spaces such as corridors, entrances, and stairs, 7 service rooms.), are distributed over three floors. Both the heating and the ventilation system are connected to district heating. Most of the radiators of the classrooms and corridors are old cast-iron radiators; some of those are also under-dimensioned.

Through a server using an MQTT (**Message Queuing Telemetry Transport**) publish-subscribe network protocol, we established a two way connection to the HVAC system. Hence, we are able to monitor the HVAC system and eventually change set points of the inlet temperature both in the ventilation as well as in the heating system. Moreover, we can turn on and off the ventilation system. On some radiators, we installed sensors to monitor the outlet temperature. Through energy meters, we monitor both electricity and heating energy use. In February 2019, we installed 65 smart thermostatic valves, and six gateways, to control the set temperature of each single radiator/room.

Figure 3. Facade of the building of the school.

Online monitoring platform: Climify

TRUST and *EFFORT* are connected, since our willing to make an effort to retrofit a building is proportional to the trust we have in the benefit that such a retrofit solution would bring. Transparency is a key component of *TRUST*: being transparent means to provide an access (to the buildings' owners/occupants/managers) to the raw data and to pre-evaluated data of the buildings, related to the indoor environment, and related to the energy use.

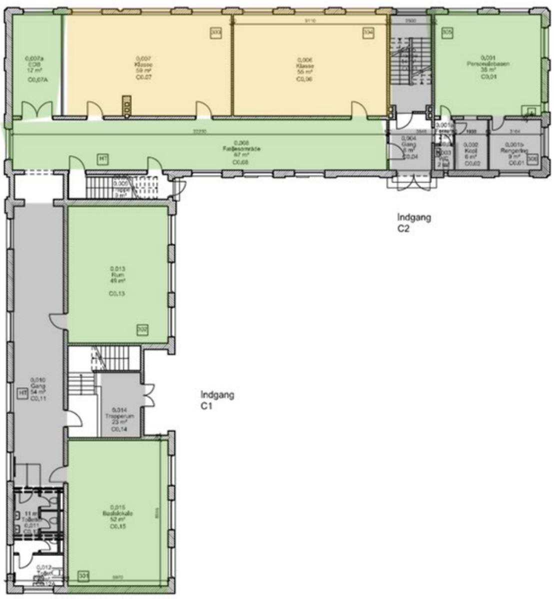

Figure 4 Qualitative evaluation of the measurements (e.g. a single measurement, such as the room temperature, or a combination of measurements, such as temperature and humidity combined) in each room, in live-stream modus.

In order to maximize TRUST and minimize the EFFORT, we developed Climify, a platform dedicated to the monitoring of buildings. Through Climify, also existing buildings with legacy systems can become a Cyber-Physical-System: Climify connects IoT devices from different vendors together.

The devices that can be connected to Climify include sensors (e.g. CO_2, temperature, humidity, etc.) and actuators (e.g. smart thermostats, smart shutters, window motors, pumps, etc.). Through Climify, the data are collected and presented to the buildings occupants, and to the buildings managers/owners. The visualization options of Climify include both qualitative (Figure 4, Figure 5) and quantitative methods.

Climify can be used to visualize issues in the built environment and check that the indoor environmental parameters and the energy use of the building are aligned to the expectations.

Finally, occupants can use Climify to exchange information (e.g. to signalize issues) with each other and with the building managers, and to learn about good practices on operating buildings (through the visualization of learning videos e.g. on the correct way to ventilate buildings).

Figure 5 Qualitative evaluation of the measurements through time (selection of day and time of day).

Feedback app: FEEDME

As discussed in the previous chapter, VOLATILITY has to do both with occupants' volatile needs, and energy volatile production. Through the app FEEDME we address the volatility of the occupants. In standard buildings, occupants interact with the built environment either by choosing set points (e.g. set points of the thermostat, of the ventilation) or by controlling actuators directly (e.g. switching on and off lights, closing or opening windows, blinds and shutters, etc.).

Recent attempt to gather the feedback from users and use those feedback in the control loop, include the use of small wall-panels with two buttons (Adolph et al., 2014): Occupants could state they were cold or warm, by pushing one of the two buttons. Preliminary studies from (Adolph et al., 2014) shows energy savings by 10% compared to manually operated thermostats. Further attempts include the use of smileys to rate the indoor environment (mostly the temperature) or a single button to signalize dissatisfaction.

All those systems have the advantage to be easily accessible to any user. However, even a single unsatisfied occupant could rate very often (not only through a revealable fast and short series of inputs, but also e.g. every hour), and hence strongly impact in the control strategy of an entire office or classroom.

Most modern system make use of mobile phone apps. Users can use their mobile phone to rate the indoor climate, and this rating is gathered by a server and potentially used in the control loop. The main advantage of those systems is related to the chance to connect a feedback to a single occupant. Those systems are, at time of writing, only in a prototype phase, and require the occupants to manually communicate their position within the building. Inserting the position of occupants manually has two main disadvantages: it is a first barrier to leave the feedback (since it makes the feedback provision operation a more complex task), and it increases chances of mistakes when choosing/typing the own indoor location.

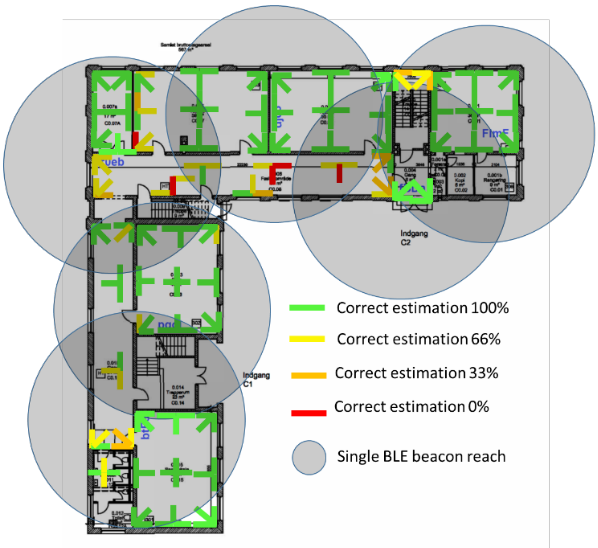

Figure 6 Qualitative evaluation of correctness of room recognition by the FEEDME app on ground floor (GF), and qualitative reach-range of the beacons installed on GF (beacons from upper floors reach also on GF, but are not visualised here).

The feedback mobile application FEEDME (open source: https://github.com/DTUFeedme/feedme-ios) is the core of our system, and it allows occupants to provide their personal feedback about the perceived indoor environment.

FEEDME differs from standard feedback apps through its location service. It uses a Bluetooth Low Energy (BLE) beacon network, and through a self-implemented classification algorithm known as k-NN, it locates the indoor position of occupants. We proved the correctness of the localization service which we could get through the FEEDME app. Figure 6 shows the validity of the localization service and the qualitative signal strength of the BLE network on the ground floor. We conducted three set of measurements in each corner, four set of measurements in the inner area of each room: The measurements are realized with an iPhone 7.

A researcher was standing at the corners and in the center of each room and was testing the correctness of the localization detection service with the iPhone, pointing the phone towards three different directions (four, when measuring in the middle of the room); For each direction (represented by a colored segment in the figure) 3 separate measurements have been conducted). The results are plotted in Figure 6: the color green indicates 100% correct detection, yellow indicates 66%, orange 33%, red 0%. As Figure 6 shows, closed rooms such as meeting rooms, classrooms and offices are mostly recognized 100% correctly. However, open rooms not always could precisely be recognized. We could have enhanced the precision of the service by ordering and then installing a larger number of beacons but decided not to do so not to slow down the study.

Once the finger printing process was done, and the localization service was enabled, we started posting specific questions to the rooms. FEEDME allows building managers to post an unlimited number of questions with a related set of pre-defined answers to specific rooms. A screenshot of the app can be seen in Figure 7.

Building Control and experimental set up

We asked the teachers about their perception of the indoor temperature in the room, and allowed them to provide 5 answers:

- “Alt for varmt” – Far too warm
- “lidt for varmt” – A bit too warm
- “God” – good
- “Lidt for koldt” – A bit too cold
- “Alt for koldt” – Far too cold

The teachers decided to provide feedback up to twice a day, when entering the rooms, the first time in the morning, and when leaving the rooms, right before leaving the school, in the afternoon. They were also allowed to provide feedback whenever they wished to do so. In total, the teachers provided 108 feedbacks in the period between the 15 of January 2020 and the 13 of March 2020 (this period includes a one-week winter holiday in February).

For the first two and half weeks of the experiment, until the 2.02.2020 (what we refer to as Period 1), we used a fixed schedule for heating the rooms.

In Period 2, from the 3.02.2020 to the end of the experiment, an operator started adjusting the temperature in each room accordingly to the teachers' feedbacks, the actual set point, and the actual temperature monitored in the rooms.

It shall be noticed that this is just a preliminary study and no systematic control algorithm has been implemented yet: the final decision on the variation of set point was in the hand of the operator.

Figure 7 Screenshot on a mobile phone of the app FEEDME related to the question "How do you perceive the indoor temperature?" and 7 possible answers.

User Incentives

The school addressed within this experiment has been in focus of several research projects related to indoor environment, heating and ventilation, since 2017.In Jan. 2019 we introduced the possibility to provide feedback, for the teachers, and we explained that this was their chance to actively decide the indoor climate of the classrooms; Moreover, to incentivize the usage of the app, and to also obtain specific feedback on the app usage, we provided, as a gift, a new coffee machine to the school (for usage among teachers only).

Preliminary Results

During Period 1, we used a fixed schedule for heating the rooms:

- 22°C during the day, between 6 am and 3 pm,
- 16°C during night.

The school is usually occupied from 8 am to 3 pm. During this time, we received 58 feedbacks, plotted in Figure 8.

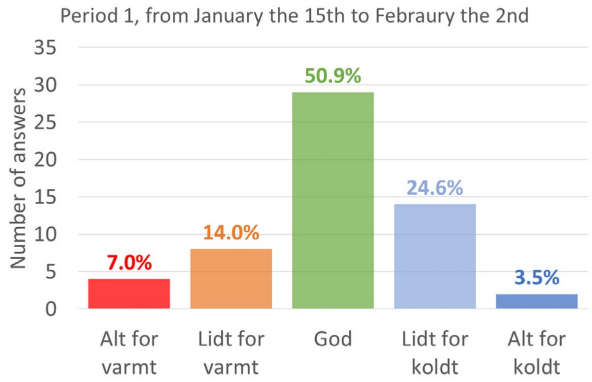

Figure 8 Number of times each single answer was given, and percentage of that articular answer for Period 1

About 51% of the answers (29 answers) were positive about the indoor climate, 21% of the answer were indicating a warm (8 answers, 14% of the total) or a too warm (4 answers, 7% of the total) indoor climate. The answer "a bit cold" was provided 14 times (24.6% of the total), while the answer "too cold" was provided 2 times (3.5% of the total).

In Period 2 we started adjusting the temperature in the rooms accordingly to the teachers' feedbacks and temperature measurements. Mapping the single answers to the single rooms, we manually adapted the set-points of the classrooms (see *Figure 9* for the number of rooms with a specific set point during daytime, after the adjustment). In one room, a very high set temperature (26°C) was necessary to satisfy the occupants: this room, particularly big and located on the first floor, has 3 big non-insulated outer walls, 3 windows, and only two radiators on one outer wall. Most of the rooms (21 rooms) had finally a set temperature of 23°C.

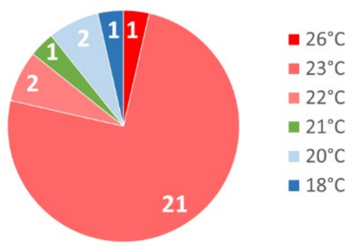

Figure 9 No. Of rooms with a specific set-temperature, at the end of Period 2.

In Period 2, over 63% of the answers (31 answers) were positive about the indoor climate, 12% of the answer were indicating a warm (5 answers, 10% of the total) or a too warm (1 answer, 2% of the total) indoor climate. The answer "a bit cold" was provided 10 times (20.4% of the total), while the answer "too cold" was provided 2 times (4% of the total).

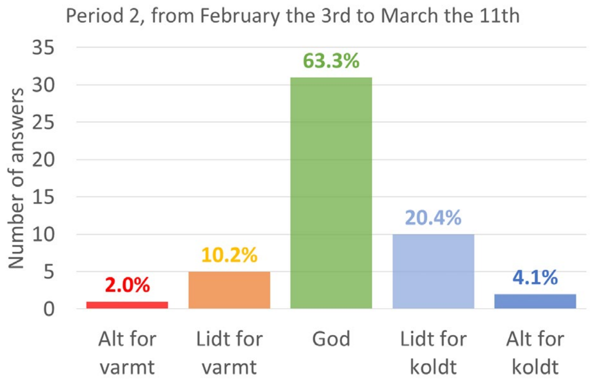

Figure 10 Number of times each single answer was given, and percentage of that articular answer for Period 2

In Period 2 teachers were generally more satisfied than in Period 1, which indicates that adopting indoor climate to occupants' feedback has a great potential. Also, the total number of answers was bigger under Period 1 (57 answers over 12 working days, 4.7 answers per day) than under period 2 (49 answers over 23 working days, 2.1 answers per day). A lower number of answers under Period 2 could indicate:

- A lower interest or engagement of the teachers in using the app, and/or
- A bigger occupants' satisfaction (no need to answer since the indoor climate is good).

Proposal of a basic control strategy

As a first stage control scheme, we present a simple adaptive control method. Whenever a teacher (or more in general an occupant) gives the feedback "cold" or "very cold", the controller increases the set-point value for the radiator(s) in the given room. Vice versa whenever a teacher gives the feedback "A bit too hot" or "Way too hot", the controller decreases the set point value. The *amount* with which the controller will increase or decrease the set-points are not trivial though and depend on the exact answer of the occupants.

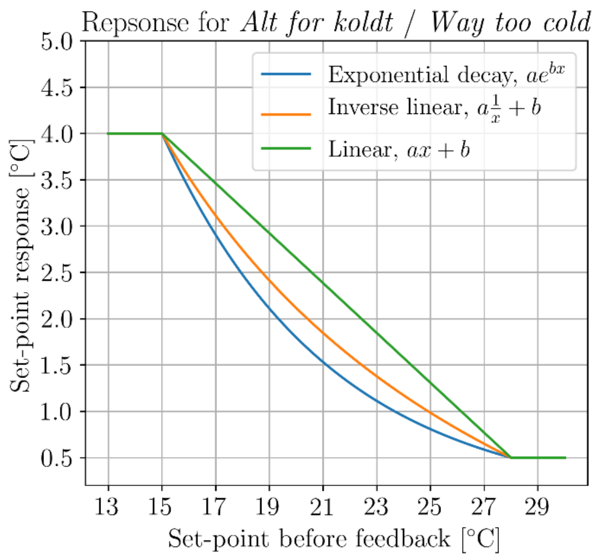

Figure 11 Response value to feedback "Way too cold"

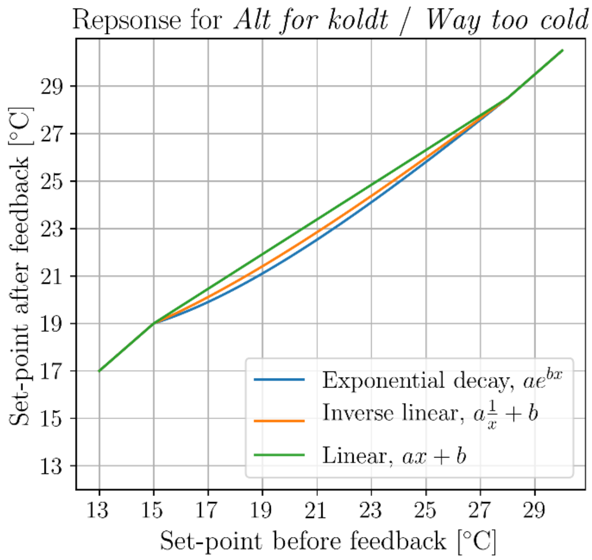

Figure 12 New set-temperature after feedback "Way too cold"

Figure 11 and Figure 12 show the so-called *response-function* for the feedback "Very cold". This is a function of the current set-point and maps the current set-point into the new set-point. In particular, Figure 11 shows the response value alone, while Figure 12 shows the new set-temperature for the response "very cold".

Both Figure 11 and Figure 12 show three possible types of functions: an exponential, a linear and a reciprocal function. They are all three doing the same: they lower (or raise) the temperature according to some scale as a function of the current temperature. The scales have different properties, e.g. the exponential decay accounts more for lower responses for higher temperatures. However, the response scale may be, and probably is, an individual preference. Future work involves learning the individual response functions from data to personalize them to each costumer.

We choose a fixed lower and upper set-point response, where the function is truncated. The maximum set-point response happens when the current set-point is already low, and increases it by 4 degrees Celsius. In the reverse case, the lowest set-point response happens when the current set point is already high, and increases it by 0.5 degree Celsius. By having these points fixed, (x_1, y_1)=(15,4) and (x_2, y_2) =(28,1), we can compute the parameters of the response function, *a* and *b*.

We choose to truncate the ends of the functions, to make sure that the response does not explode in the ends. In an extreme case, if the set-point value prior to a feedback is 5 degree Celsius, the exponential set-point response would otherwise have been around 20 degree Celsius. In general, we do not want such large jumps in the set-points. Assuming that the outdoor air temperature and other dependencies of the room air temperature changes relatively slowly, the need for set-point changes will also be of smaller magnitudes.

It shall be noticed that if the teachers supply feedback "continuously" throughout the year the set-points adapt to the heat demands. E.g. during the summer, not much heat is required. However, when transitioning from summer to winter, more heating is probably necessary in order to maintain a comfortable temperature. This, however, is also a disadvantage, since the teachers *need* to supply feedback as it gets colder – otherwise the set-points do not change, and the indoor air temperature likely gets too cold. We can avoid this problem by shutting down manually the heating system in summer, and adopting, the set points of the last used heating schedule, when the heating season restarts.

Discussion

The results shown in the previous chapter are encouraging, yet not statistically relevant. The choice of the new set points of the smart thermostats was was a manual process, and was based on feedback and on the interpretation of the indoor temperature measurements from a single operator. Objective results can only be obtained in a systematic study, where also the definition of the new set point is done through an automatic and standardised process. Also, other effects such as the potential placebo effect and outside influences of the occupants should be considered in future studies – e.g. by using a balanced experimental design.

In the future, we would like to set up a more sophisticated control approach using among other things, comfort models of occupants, grey-box models (e.g., continuous-time models based on stochastic differential equations that describe the thermal dynamics of buildings) or AI models (machine learning algorithms, black-box buildings models, describing the dynamics of the rooms and advanced weather forecasting models. In this way, we could:

- Take personal preferences and presence into account, when choosing actual set points (e.g., by recording personal preferences and objective measurements into personal Comfort-IDs of the occupants);
- Predict preferences and presence of the occupants, and use the prediction in the MPC of the thermostats.
- Decide the right time to activate the heating of each single room, to achieve the needed temperature at the time when occupants arrive.

Nevertheless, this study shows a general higher satisfaction related to the indoor temperature, of the teachers, when taking their personal feedback into the control loop.

A main open question is related to room-control vs. personal control: should the feedback of several teachers be used to provide a generic, all day long set point for a specific room, or should the set point of a specific classroom vary with time, depending on the teachers presence schedules. The FEEDME app is able to track occupants within the buildings, and is hence able to personalise indoor climate accordingly to the needs of the individuals.

Smart thermostats have several advantages, allowing for a better indoor climate control at room level. A common problem of public buildings is related to the use of thermostats. Often, when rooms have several thermostats, several occupants can change the settings of each single thermostats. Before we installed the smart thermostats, in many classrooms, we could detect different cases where one out of three thermostat was closed, one was completely open, one on a middle position; As a consequence, the indoor climate was bad (big asymmetries in the heat delivery) and the return temperature to the district heating was high, and with a high volume flow (caused by the thermostats open at max.). Smart thermostats alone, however, don't solve all the issues in public buildings, where single users (e.g. pupils in schools or visitors in public buildings) can still change the setting of single thermostats ruining both indoor climate and energy performance. In this context, an app such as FEEDME can help in extending the advantages of smart thermostats, a product standardly thought for home-usage, also to non-residential buildings.

Moreover, a deep knowledge of the occupants needs connected to the occupants presence patterns can help in predicting building needs and maximising the flexibility potential offered by buildings to the energy grids (Junker et al., 2020, 2018; Molitor et al., 2012). In this context, occupants behaviour models (Calì et al., 2018, 2016a; Haldi et al., 2017; Wolf et al., 2019) might be useful to understand and cluster occupants preferences; those models could be used in the HuiL-based control of buildings, and also within the simulation of buildings' performance.

Conclusion

Technologies increased exponentially our opportunities: we can have nearly any light colour in our houses, through connected, smart LED bulbs, we can listen to any music just surfing in a music streaming app, we can control the daylight through smart shutters and blinds, set schedules for our thermostats, plugs, and even for opening and closing automatically windows. The world of automation is at our hands, mostly in our mobile phones. However, the number of options are very high, and most systems are trying to offer solutions that try to understand our needs and our preferences, adapt to our needs. A clear example of it is a brand-new shuffle-function of Netflix that reacts differently for each user profile. This show that users generally appreciate to have some control, but also appreciate automatic profiling of their needs (even if this means to lose some privacy, by sharing preference-related data). In the case of indoor environment, the choices to be taken are many, and are complex. A perception-based HuiL control brings together the advantages of automation, with the advantages of letting the "control" in the hand of the occupants, occupants are more satisfied, as demonstrated through this preliminary study, and is therefore the way to go in the future.

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